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SOME RESULTS OF A STUDY OF THE EFFECTIVENESS AND COST OF A LASER-POWERED "LIGHTCRAFT" VEHICLE SYSTEM

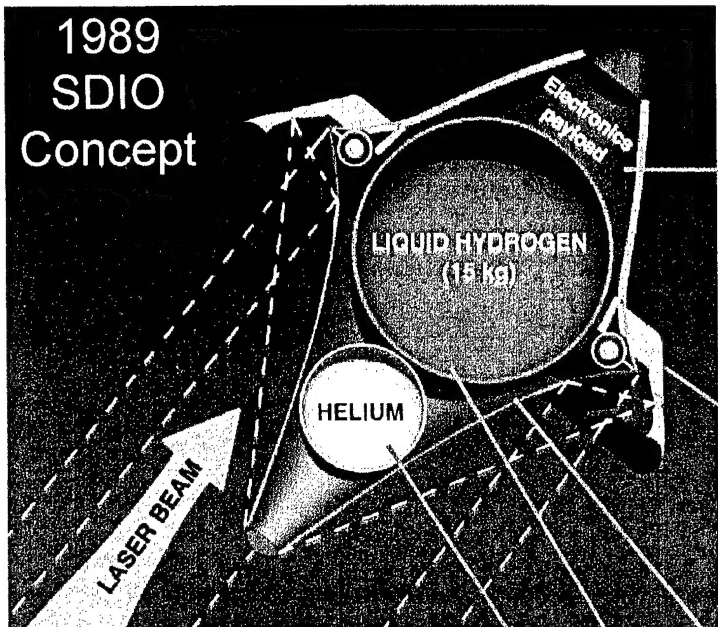
SPIE International Conference
High-Power Laser Ablation 2004
25 - 30 April 2004

By Mead, Froning, Larson, Pike, McKinney & Hasson
Work Performed by Flight Unlimited, Flagstaff, AZ
Under the Direction of the Propulsion Directorate
Air Force Research Laboratory, Edwards AFB, CA

Presentation Outline

- Background Information
- Lightcraft Technology Demonstrator (Completed Dec 98)
- Experimental 50-cm Laser Ramjet (In Progress)
  - Program Collaborations
    - Video
    - Launch model results
    - Beam propagation model results
    - International research on fuels
    - Impact of a 100 kW CO_2 laser
- Summary

The Lightcraft Concept



- A Lightcraft is a small spacecraft; diameter is ≤1.0 m, weight is ≤ 8.0 kg (~2.0 kg payload)

Forebody

- ➤ Aerodynamically contoured surface
- ➤ Analogous to rocket payload bay; opens in space to release payload and expose solar cells

Shroud

- ➤ Centrally located "belt"
- ➤ Analogous to rocket combustion chamber; ejected plasma provides thrust

Afterbody

- ➤ Analogous to rocket nozzle; parabolic mirror and plug nozzle (resolution: 7 to 15 cm in LEO)

Large tank holds liquid propellant (N_2, NH_3, or H_2) for use in space

Small tank holds gas (He) for attitude control

Why Laser Propulsion?

Benefits

- Heavy propulsion system components stay on ground
- Higher performance potential than chemical rockets
- Higher thrust than electric propulsion concepts
- None of the polluting or radioactive exhaust associated with chemical or nuclear rockets
- No physics breakthroughs required
- Repeatedly shown to be economically viable
    - AF, NASA, and DARPA have all done independent studies
- Fundamental change in infrastructure required to launch to orbit

Draw Backs

- Requires expensive, high power pulsed laser which is not currently available
- Lacks complete demonstration after 35 years from conception

Huge potential to realize low cost access to space for small satellites!

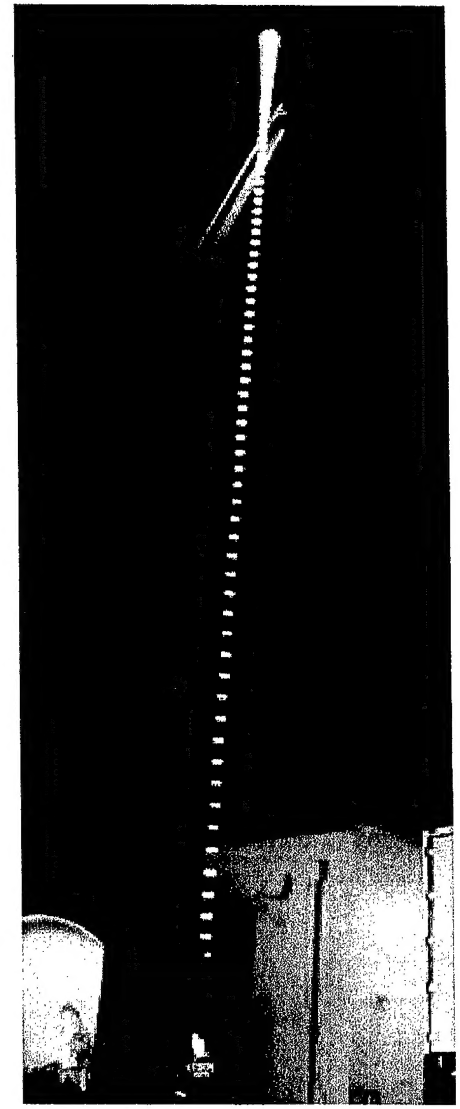
U.S. Air Force Program For Laser Propulsion Development

- <u>Lightcraft</u> Concept Demonstration
  - Four-year effort (Jan 95 – Dec 98)
  - Demonstration of the BMDO Lightcraft concept with small-scale vehicles
  - Used PLVTS, 10 kW laser at White Sands Missile Range

- **X-50LR Test Vehicle**
  - **Nine-year effort (Jan 99 – Oct 08)**
  - **Vertical launches to space (~30 km) of eXperimental 50-cm Laser Ramjet (X-50LR) from White Sands Missile Range or other appropriate sites**
  - **Requires expensive 100 kW class laser and 3 meter beam director to meet objectives**

Accomplishments
Lightcraft Concept Demonstration

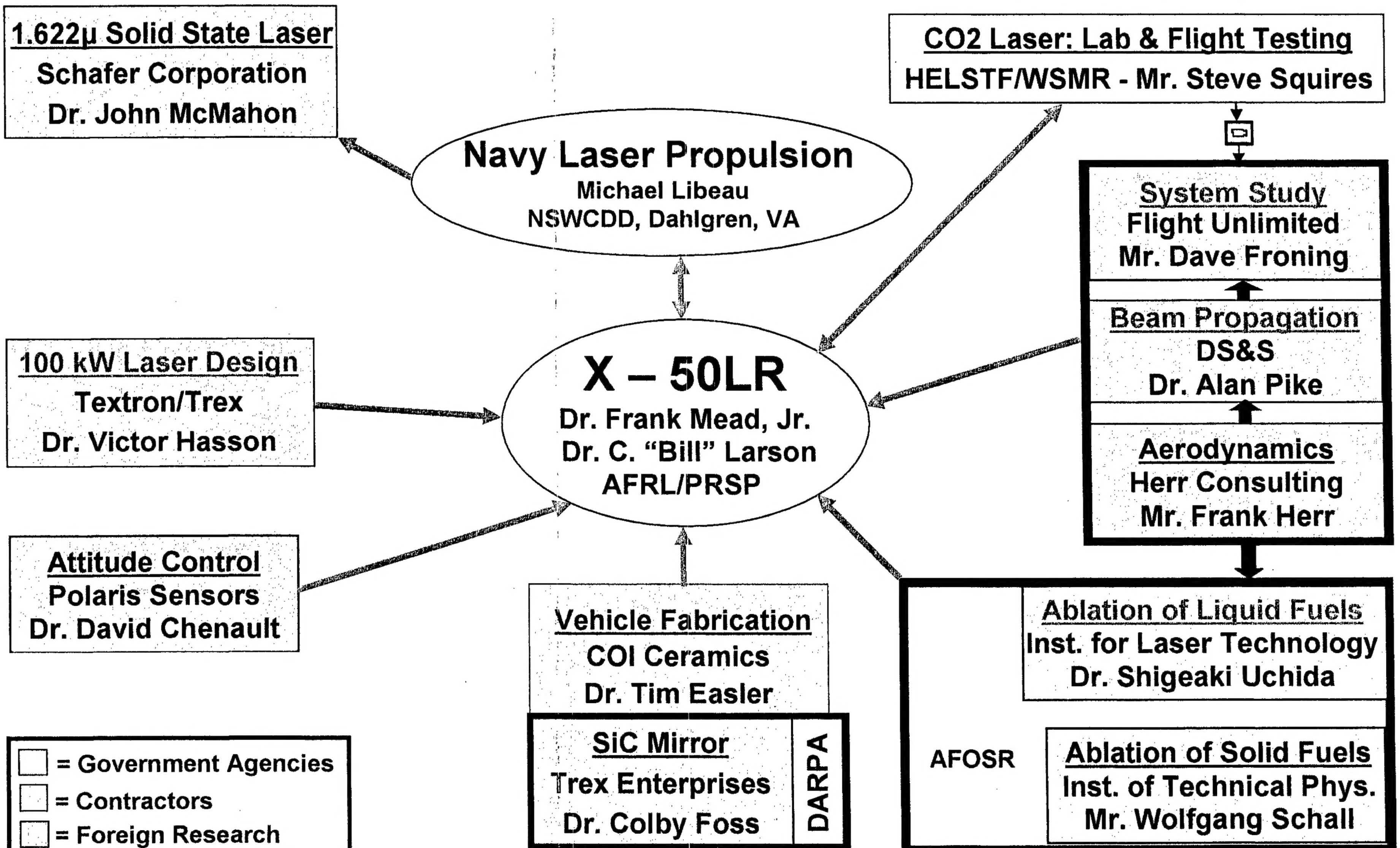
Feasibility of the Lightcraft concept was demonstrated through a series of successful, historic flight tests



- Characterized the lightcraft:
  - Conversion of laser energy to impulse
  - Measured efficiency (coupling coefficient)
- Lightcraft geometry optimized
- Pointing and tracking system demonstrated on horizontal (wire-guided) flights to 400 ft (122 m)
- First-ever outdoor vertical free flights accomplished, approaching 100 ft (30 m)

Phase II Program Collaborations

X-50LR: Experimental 50-cm Laser Ramjet



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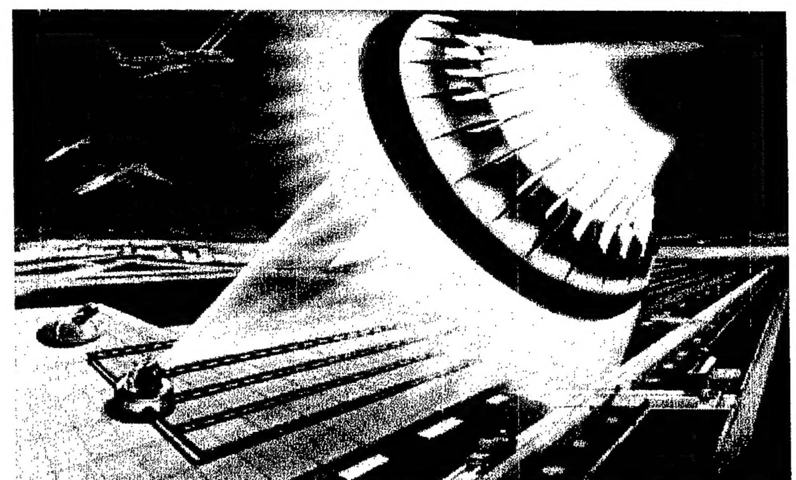
X-50LR Program Summary

- Feasibility demonstrated through a series of historic flights and experiments
- Some technology advancements for:
  - Propellants & vehicle fabrication techniques
  - Megawatt class, 1.62μ/1.06μ, solid state lasers needed soon
- Composite materials & 100 kW CO_2 laser can enable vertical flights to the edge of space within a few years
- High power lasers are useful for propulsion demonstrations
- Support for a joint services program is badly needed

Taking us from here ...

... To there.

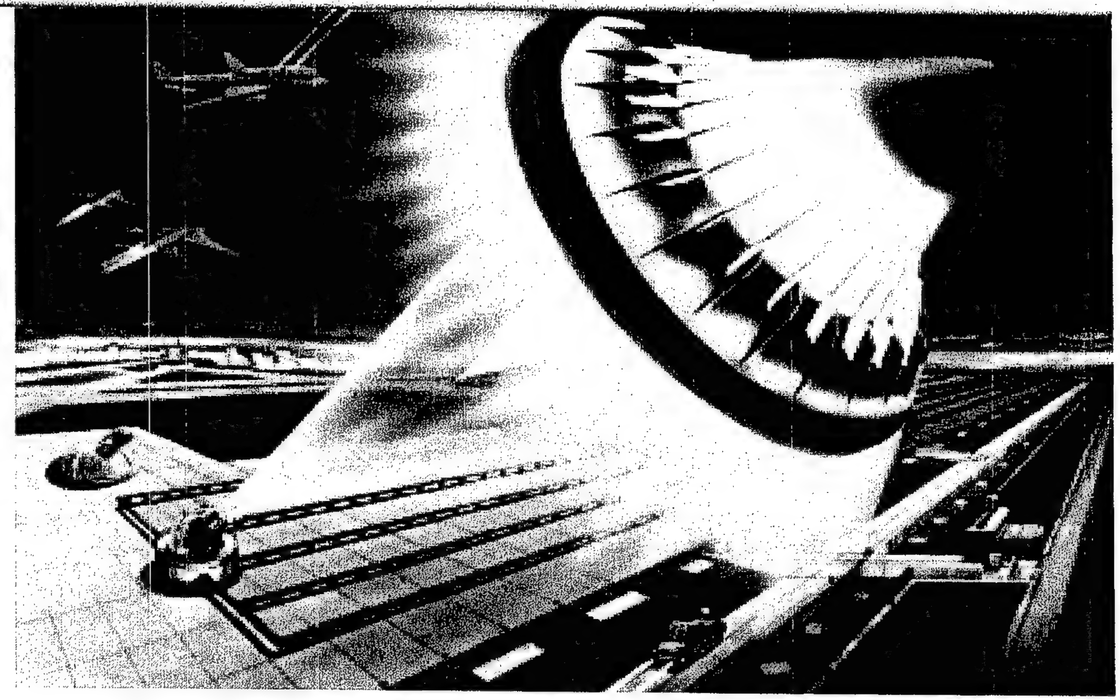


Laser Propulsion technology has the potential to make low-cost access to space a reality in the near future

The End

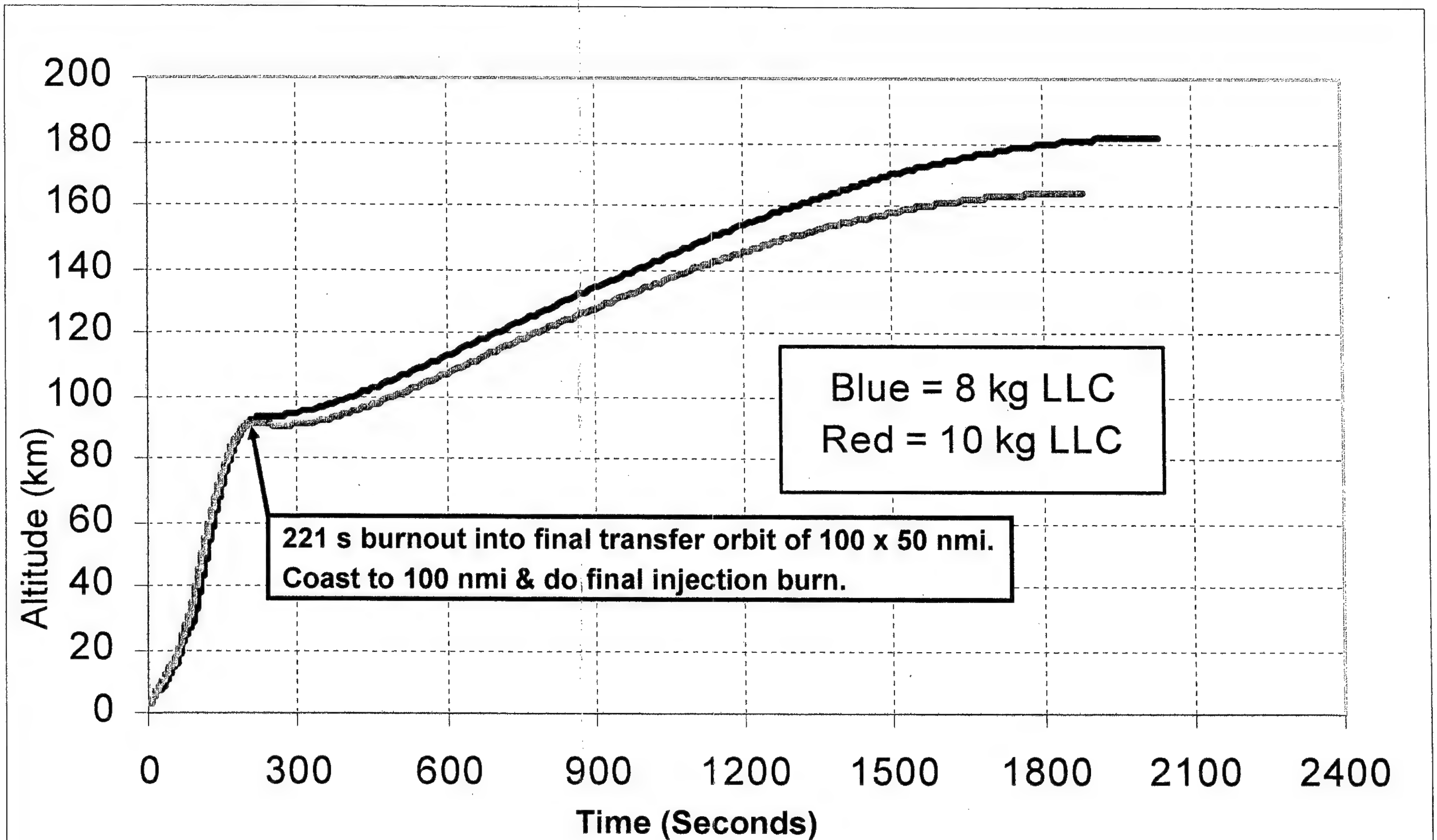
Low Cost Access To Space:
The Primary Lightcraft Application

- Laser-propelled beam rider
  - ➢ Rides ground-based laser beam into space
  - ➢ Single stage to orbit
  - ➢ Very high performance
  - ➢ Airbreathing in atmosphere, uses propellants in space
  - ➢ Launch on demand to anywhere in low Earth orbit



- Simple, reliable, safe, environmentally clean
- Launch rate of 1,000 per year achievable with solid state electric laser
- Vehicle production cost estimated at $3,760 per vehicle
- Interest in this concept expressed by AF, Army, NASA, Navy, & NRO

Launching to Orbit



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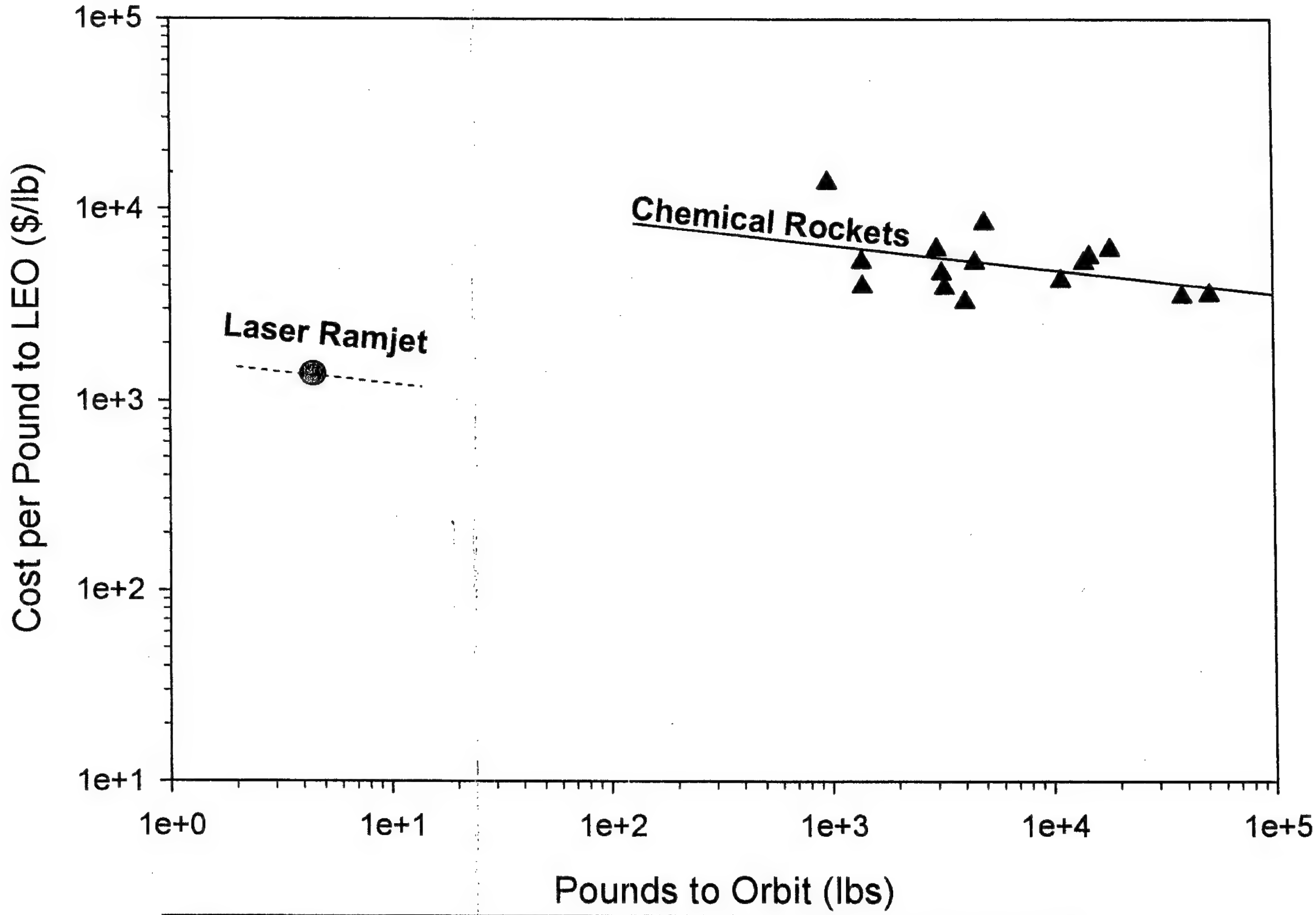
Vehicle Mass Breakdown

- Laser Propulsion Propellant .... 4.00 kg
- Orbit Circularization Propulsion .... 0.46 kg
  - Thruster (400 N) .... 0.408 kg
  - Propellant (MMH/MON) .... 0.042 kg
  - Propellant Tank .... 0.010 kg
- Airframe/Structure .... ~0.63 kg
  - Nose Tip .... 0.025 kg
  - Nose Cone .... 0.314 kg
  - Shroud .... 0.208 kg
  - Optics .... 0.079 kg
- Guidance/Control/Power .... 0.45 kg
- 30% Contingency .... 0.46 kg
- Payload .... 2.00 kg

Laser Vehicle Takeoff Weight .... ~8.00 kg

Comparison of Launch Costs to LEO



Cost Per Pound Comparison of Launch to LEO

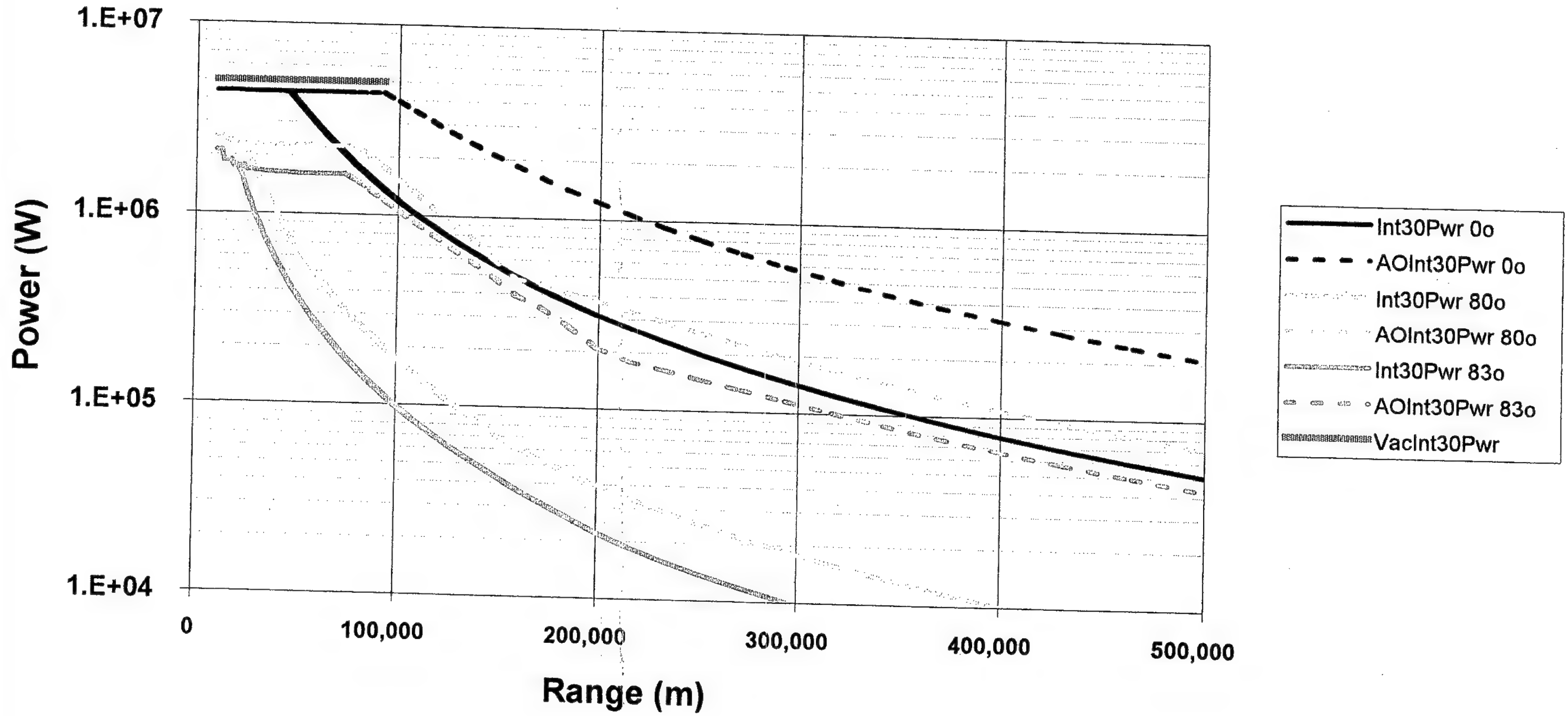
Launch Vehicle*	Lift Capability (100 NM, 28.5°)	Launch Price	Cost per Pound
Laser Ramjet	4.4 lb	$6,105 K*	$1,388
Pegasus	1,000 lb	$7 - $12 M	$7,000 - $12,000
Taurus	3,200 lb	$15 M	$4,690
Titan II	5,000 lb	$43 M	$8,530
Delta 7925	11,100 lb	$45 - $50 M	$4,050 - $4,500
Atlas II	14,100 lb	$70 - $80 M	$4,960 - $5,670
Atlas IIA	14,900 lb	$80 - $90 M	$5,370 - $6,040
Atlas IIAS	18,500 lb	$110 - $120 M	$5,950 - $6,490
Titan IV	39,000 lb	$154 M	$3,550
Shuttle	51,800 lb	$130 - $245 M	$2,510 - $4,730

*The chemical rocket values are taken from Air Force Spacecast 2020

* Shared Laser Costs

Isotopic CO_2 Laser Can't Launch to LEO

(Beam Propagation as a Function of Wavelength)



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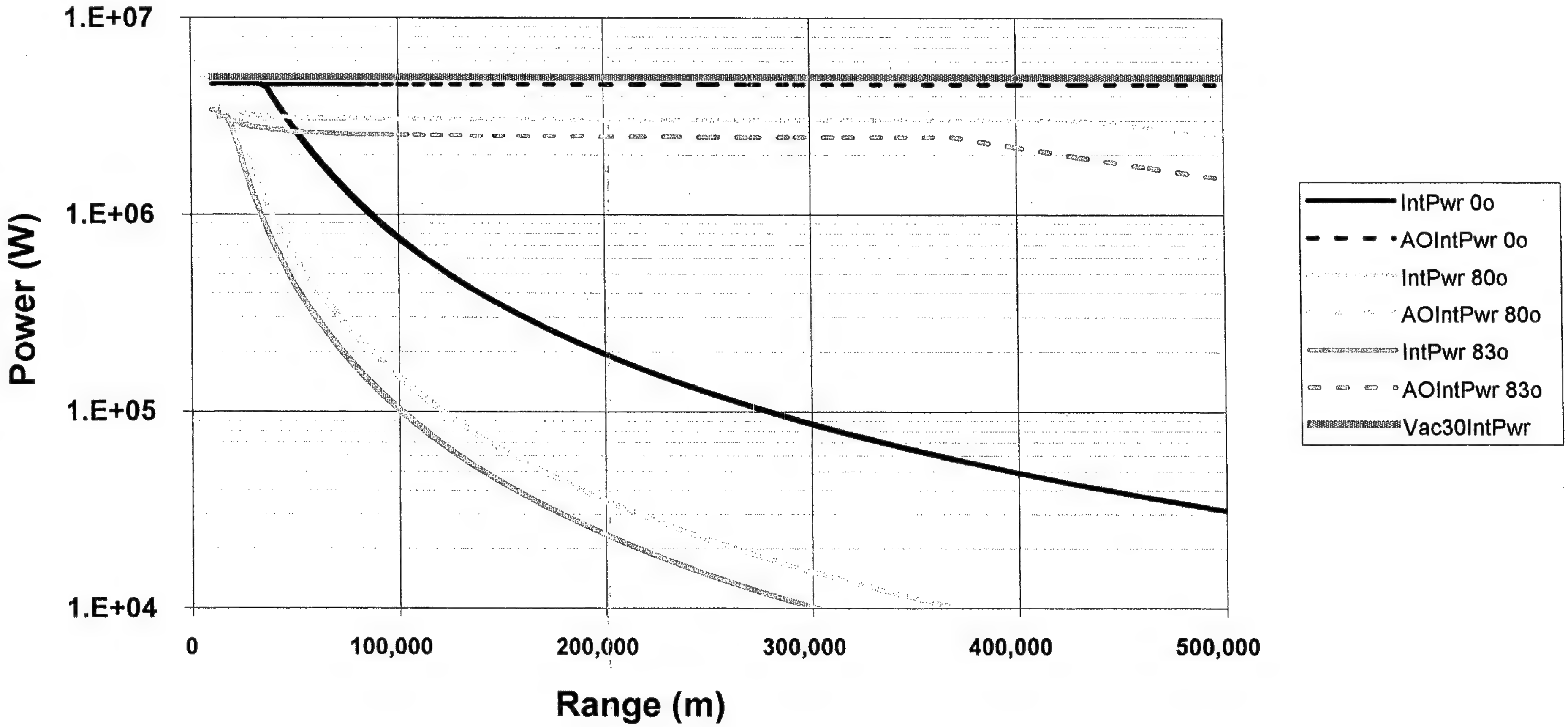
Solid State Laser Can Launch ~5 kg

(Beam Propagation as a Function of Wavelength)



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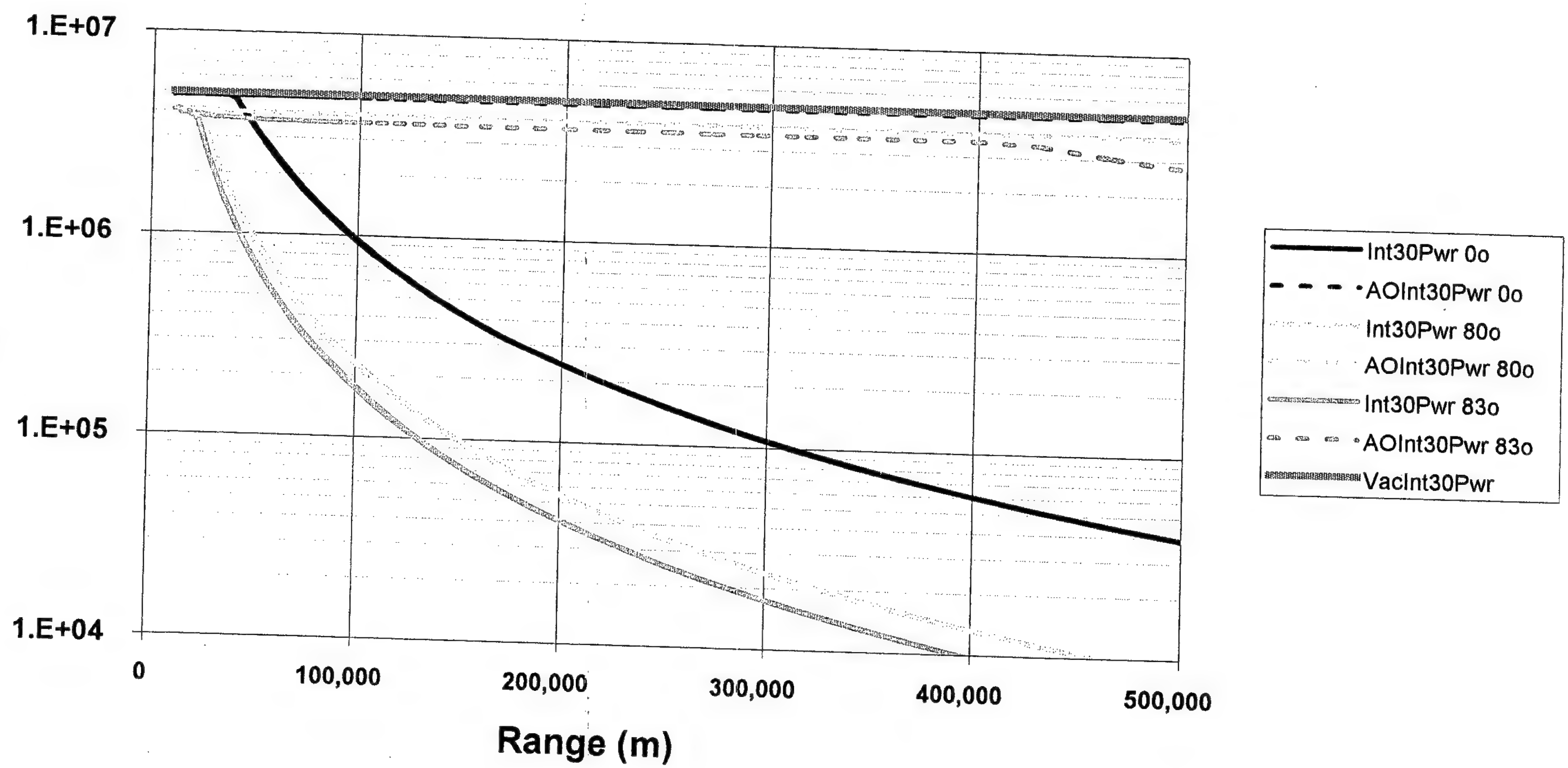
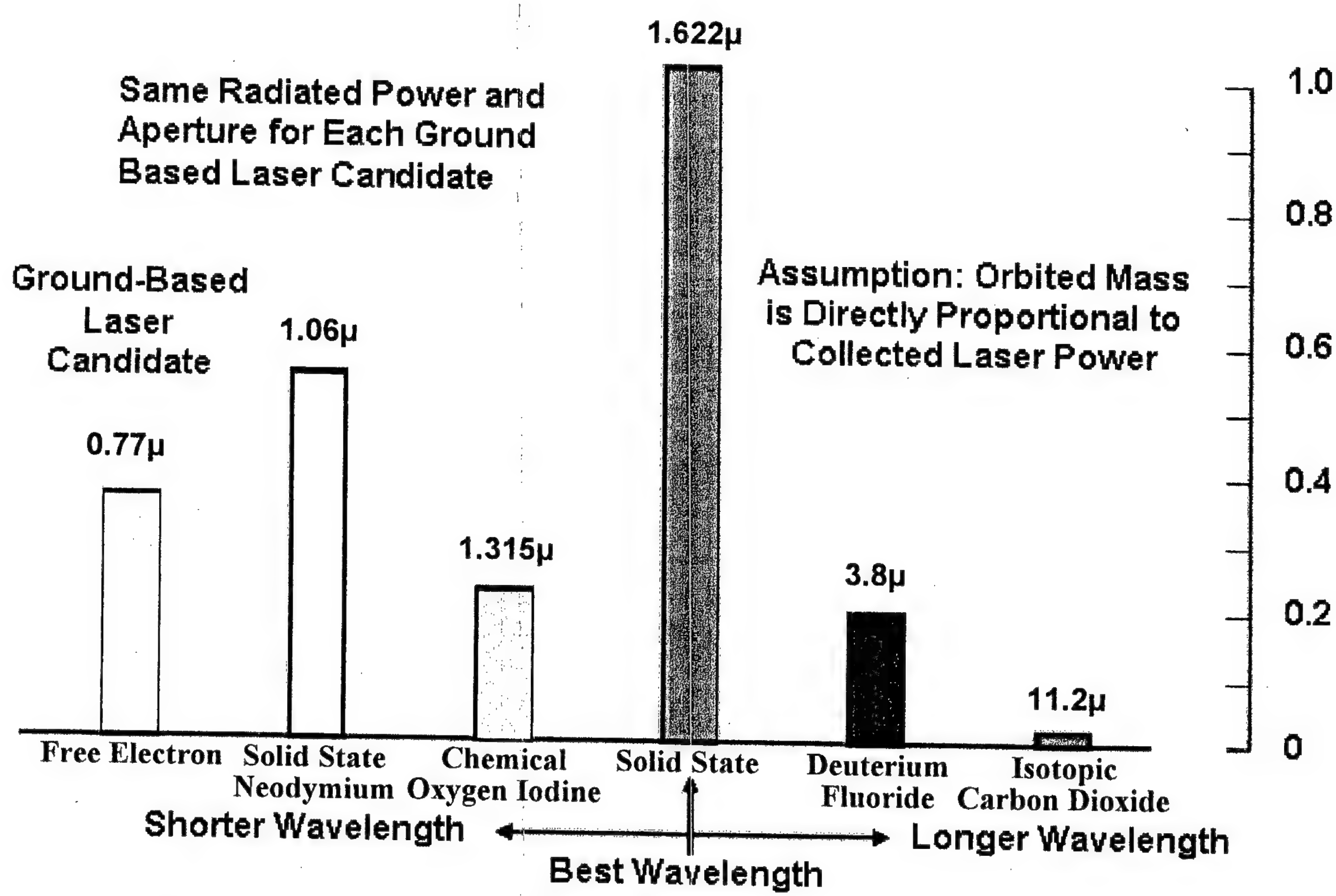
Navy Solid State Laser Can Launch 8 kg

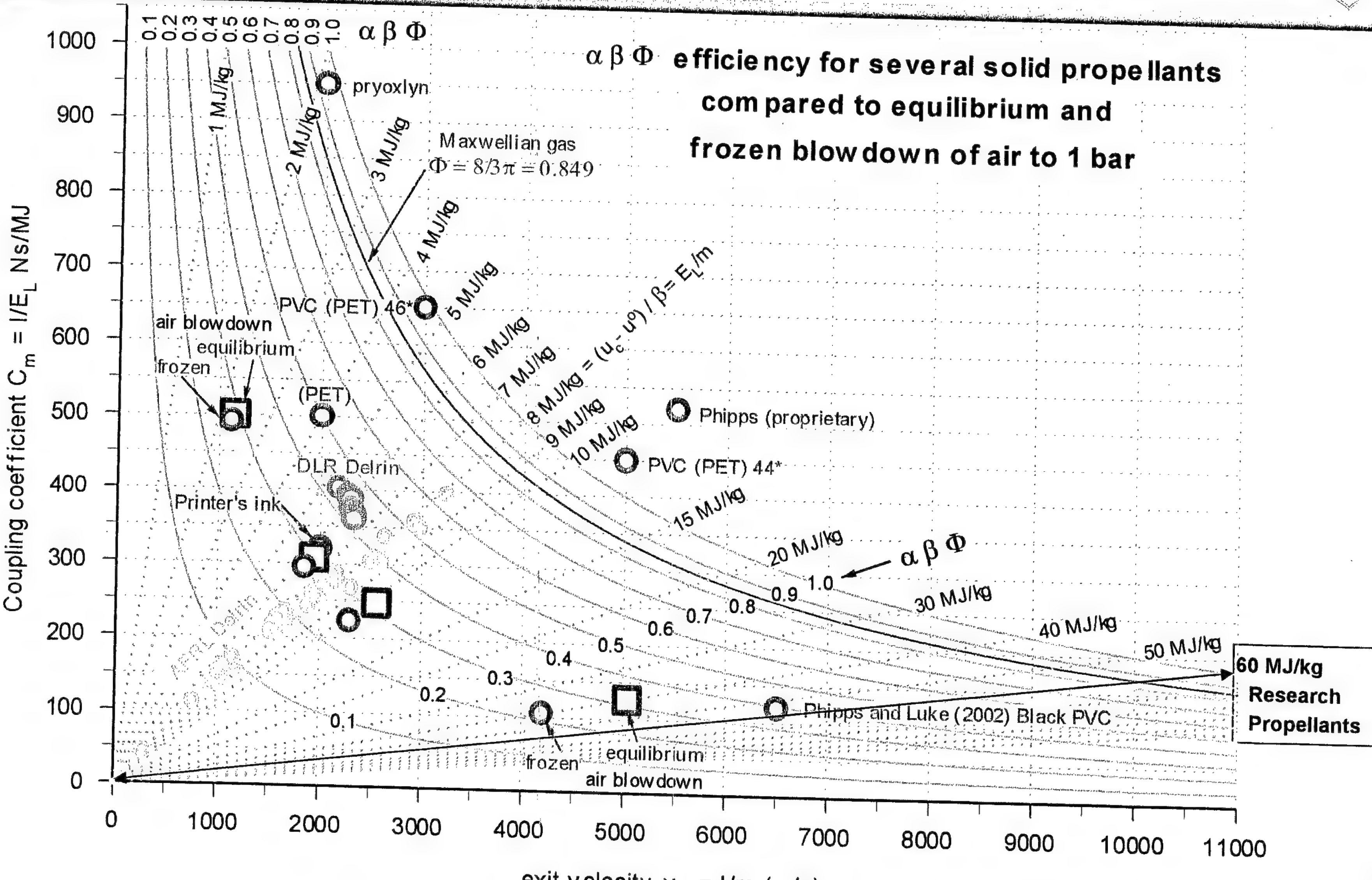
(Beam Propagation as a Function of Wavelength)



Impact of Laser Propagation on Mass to Orbit



Performance Map of Known Laser Materials



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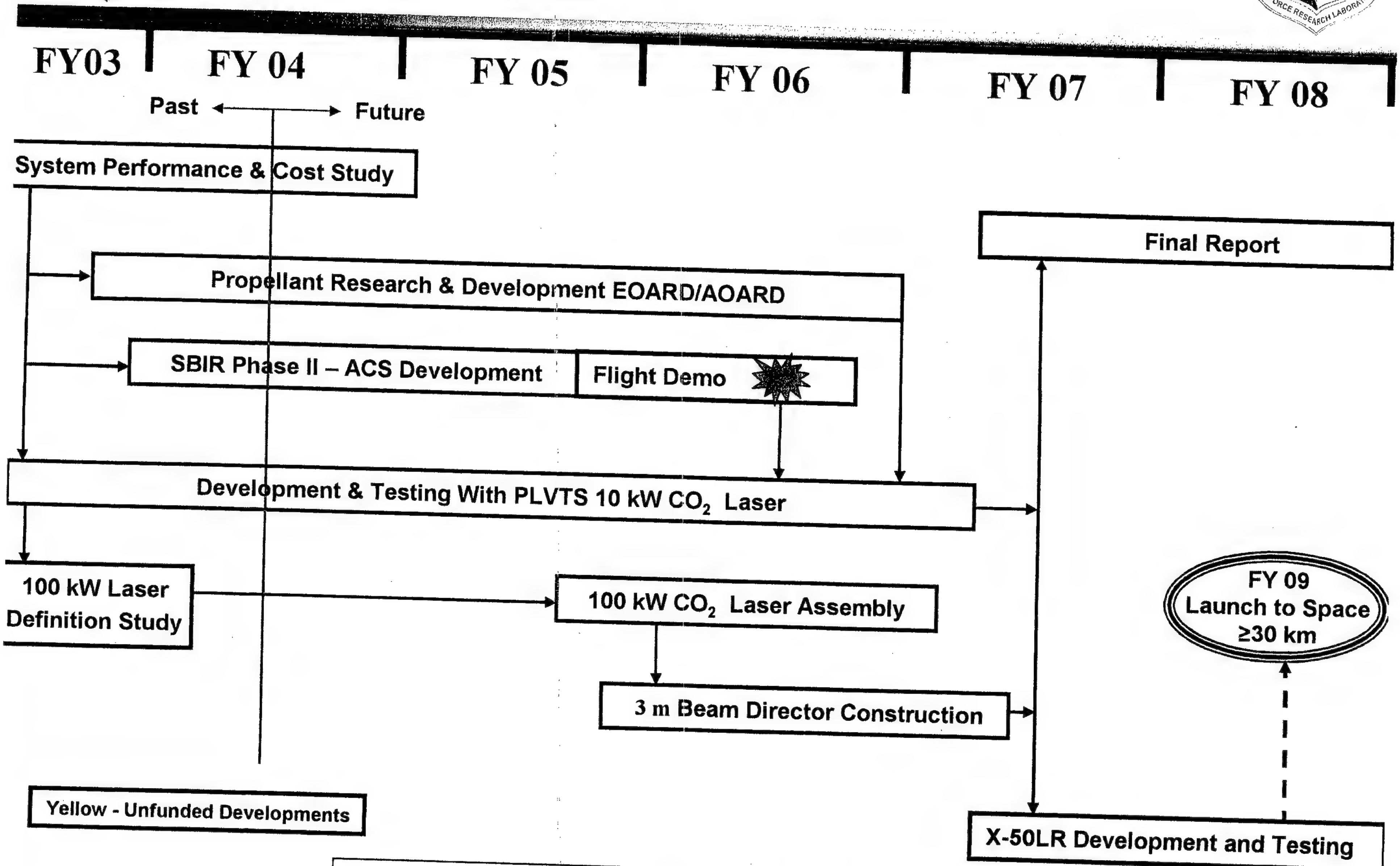
X-50LR Development Opportunities
(Phase II)



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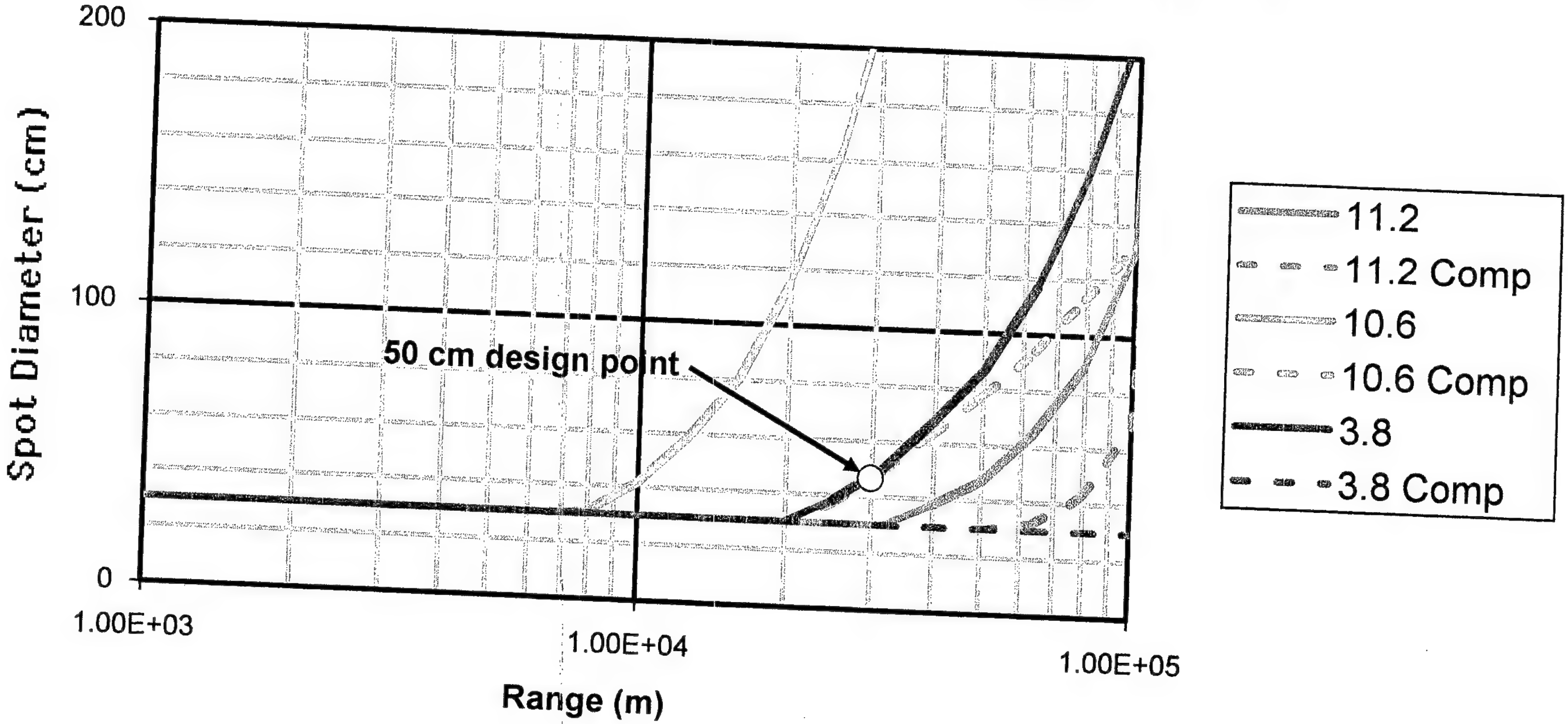
CO_2 Laser Can Do 30 km Mission

(Beam Propagation as a Function of Spot Size)

Spot Size Versus Range

10.6μ CO_2 Laser & 3 m Beam Director can do 30 km Mission with X-50LR



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Some results of a study of the effectiveness and cost of a laser-powered "lightcraft" vehicle system

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ABSTRACT

Laser-powered lightcraft systems that deliver microsatellites to low earth orbit have been studied for the Air Force Research Laboratory. One result of this study has been discovery of the significant influence of laser wavelength on the power lost during laser beam propagation through Earth's atmosphere and in space. Here, energy and power losses in the laser beam are extremely sensitive to wavelength for earth-to-orbit missions. And this significantly affects the amount of mass that can be placed into orbit for a given maximum amount of radiated power from a ground-based laser.

1. INTRODUCTION

The laser ramjet concept is a revolutionary and radical departure from chemical rocket technology. Laser ramjets use air as a propellant up to an altitude of ~30 km and on-board propellants at higher altitudes and in space. Ascent propulsion is provided by the projection of laser energy from a high power ground-based laser (GBL) through a large diameter beam director. The laser ramjet receives the laser energy and converts a propellant, which can be either air or some other working fluid carried on-board, into a high temperature and pressure plasma (i.e., laser ramjet propellant energy densities are at least an order-of-magnitude beyond the present limits of chemical combustion) through the use of a concentrating, parabolic shaped, reflecting surface at its rear. The laser launch facility is initially expensive; but it stays on the ground, is never at risk during launch, and is reusable thousands of times.

The entire infrastructure required to launch a laser ramjet will have <u>no</u> resemblance to that used for today's chemical rockets. No huge motorized tractors to move vehicles, no skyscraper gantries, or standing army of mechanics and technicians. There will be no toxic fuels, no explosive hazards, and no large propellant farms. Laser ramjets will be wheeled to the launch stand on small carts from a nearby clean-room (i.e., where dozens of vehicles are assembled, stored until they are needed, and pre-launch servicing and checks-outs occur) and lifted gently onto a launch platform by two or three persons. The launch from the laser control room will be quick and easy. A laser operator pushes a button to initiate the launch sequence, and at time zero the laser ramjet lifts-off and accelerates directly into LEO as a single-stage-to-orbit vehicle.

The Lightcraft Technology Demonstrator (LTD) (See Fig. 1) was a laser propelled trans-atmospheric ramjet concept developed at Rensselaer Polytechnic Institute (RPI) for Lawrence Livermore National Laboratory and the Strategic Defense Initiative Office (SDIO) Laser Propulsion Program in the late 1980's.[1] This laser launch concept was envisioned to employ a 100 MW-class GBL to transmit power directly to the Lightcraft in flight. An advanced, combined-cycle engine was to propel a 120 kg, 1.4-m diameter LTD, with a mass fraction of 0.5, to orbit.

The LTD concept was a nanosatellite in which the laser propulsion engine and satellite hardware are intimately shared. The nose cone was an aerodynamically countoured surface, and analogous to a rocket's payload bay, opened in space to release its payload and expose solar cells located on the inside. The shroud is the centrally located "belt" around the center of the vehicle. It is inside the shroud, analogous to rocket combustion chamber, that a high temperature plasma is created from focused laser light. It is the ejection of this very hot gas to the rear that provides the thrust. The aft parabola had a dual function as a primary receptive optic for the laser beam and as an external expansion surface or plug nozzle.

Once in space the LTD vehicle was to become an autonomous sensor satellite capable of delivering precise, high quality information typical of today's larger orbital platforms. Here, the 1-meter diameter parabola was to serve as an optical telescope or receiving/transmitting antenna for a low power laser or microwave communication system.

In 1996, the Air Force Research Laboratory's Propulsion Division at Edwards AFB initiated a program based upon the 1989 LTD design. The initial effort, called the Lightcraft Technology Demonstration (LTD), was to demonstrate the feasibility of the basic idea as a subscale prototype. Figure 2 is an artist's conception of the model that was developed and used for flight testing during this effort. This figure shows the laser light coming from the lower left impinging on the parabolic surface and being focused in a circular ring on the inside of the shroud where the intensity is sufficient to form a high temperature, high pressure plasma which then expands out the back to provide an impulse for each pulse of the laser. The laser repetition rate multiplied by the single pulse impulse then represents the mean thrust. As illustrated in figure 2, the inside of the vehicle is hollow, and the aluminum walls are very thin (i.e., ~10 to 12 mils). The total weight of a flight vehicle is about 30 g. Figure 3 is an integrated light picture of the plasma ejection from an LTD vehicle.

This initial demonstration was successfully completed in October 1998. With a variety of vehicle sizes, all laser testing was conducted at the High Energy Laser Systems Test Facility (HELSTF), White Sands Missile Range (WSMR), New Mexico,.using the 10 kW, Pulsed Laser Vulnerability Test System (PLVTS), CO_2, electric discharge laser. The basic conclusion of the work was that the feasibility and basic physics of the Lightcraft concept had been adequately demonstrated. Under the LCD effort, performance was measured with a pendulum impulse test stand that allowed the characterization of the concept's coupling coefficient and impulse per pulse of laser light, a pointing and tracking system was developed and demonstrated on horizontal wire-guided flights outdoors to 400 ft (122 m), and outdoor vertical free-flights approaching 100 ft (30 m) were successfully conducted.[2,3,4] Low Mach number wind tunnel tests were also accomplished with a 23-cm diameter model, and later reported.[5]

2. Current Program Status

The follow-on effort entitled the Experimental 50-cm Laser Ramjet (X-50LR) Program is currently in progress and has as its major goal the launching of 50-cm, functional, laser-propelled vehicles, from WSMR, in sounding rocket trajectories, to altitudes above 30 km (~18 miles) by the end of fiscal year (FY) 2009 using a 100 kW CO_2 laser. However, the 100 kW laser does not currently exist, and the plans to assemble this laser using three lasers that are storaged at WSMR and the operational PLVTS laser will be discussed below.

The current work under the X-50LR program involves scaling up from the smaller 10-cm aluminum vehicles, used so successfully during the previous LTD program, to an experimental 25-cm laser ramjet (X-25LR) vehicle.[6,7] The X-25LR vehicle is made of lightweight composite materials with fully functional air inlets. For the first time, electronics and attitude control (i.e., both lateral and angular pointing) are being added to a laser flight vehicle which is anticipated to allow flights to altitudes of at least 1,000 feet.

The program involves a strong team of Government and contractor participants. Figure 4 illustrates the collaborators and participants in the X-50LR program. Government participants are shown in yellow, contractors are shown in blue, and foreign participation through the Air Force Office of Scientific Research are shown in green.

The HELSTF, WSMR, New Mexico, is the premier laser testing facility for all of the DoD. It is operated by the U.S. Army. All testing to date has been accomplished using the available 10 kW, PLVTS, CO_2 electric discharge laser.[6] Single pulse laboratory tests are accomplished inside the Test Cell 3 building with heavy weight bench models mounted on a pendulum that measures impulse from single laser pulses. Outdoor vertical flight tests are launched from the rear of the laboratory on a cement slab. For experiments with the 10-cm aluminum vehicles, the laser has typically been operated at 25 pulses per second with 18 μs pulse widths. Flight tests durations over three seconds with Aluminum vehicles during the LTD effort resulted in the destruction (e.g., melting due to extreme heat) of the shroud, thus limiting flight altitudes to about 100 ft. To avoid this problem, an ablative propellant, Delrin, was inserted into the shroud area to provide cooling. The addition of Delrin propellant has allowed a significant extension the flight times, and thus the attainment of much higher altitudes (i.e., to several hundred feet). But using a propellant in the atmosphere has always been considered as an interim approach until high temperature materials, that can sustain the high temperatures encountered, can be incorporated into the vehicle construction.

At the beginning of fiscal year 2001, a study program was initiated with Flight Unlimited in Flagstaff, AZ, to determine if lightcraft vehicles powered by energy beamed from ground-based lasers can cost effectively perform future Air Force missions, and to provide parametric models for exploring the potential of lightcraft and laser systems

for the estimated range of laser propulsion efficiencies that appear achievable.[7] This study was designed to take advantage of the extensive laser propulsion technology that had been developed by theoretical and experimental work of the Air Force Research Laboratory and others. For the first time, experimental data with an actual laser rocket was used in a performance study.

Flight Unlimited was specifically directed to study the "Low Cost Access to Space" mission as illustrated in Figure 5 which illustrates a laser propelled ramjet being launched to space. This concept uses a laser propelled beam rider, single stage-to-orbit (SSTO) vehicle which utilizes only air to an altitude of about 18 miles (30 km) and a propellant above that altitude and in space. It is a "launch on demand" concept to any azimuth in low-Earth-orbit (LEO). The concept is simple, reliable, safe, and environmentally clean. The study modeled the cost based on a launch rate of 1,000 per year with a solid state electric laser. Vehicle production costs were estimated at $3,760 each, and launch costs of $6,105 per launch.

For the Flight Unlimited study, the AFRL's Propulsion Directorate studied the propagation of high power laser energy focused at long ranges through the atmosphere with Dr. Alan Pike of DS&S. A number of laser wavelengths at identical radiated power and aperture were examined. The selected wavelengths were representative of high power lasers systems either currently under development or available. Using those values and their detailed propagation model, Defense Strategies & System Inc., calculated the expected irradiance and far field beam diameters as a function of transmitted power, range, beam director diameter and zenith angle, with and without adaptive optics.

The analysis was performed under varying atmospheric conditions using models developed by Dr. Pike. Atmospheric variations differed mainly in the amounts of aerosols present at high altitudes. The analyses included the combined effects of thermal blooming, turbulence, and linear extinction. The study also included the effects of laser beam quality, transmitter optics quality, and pointing jitter of the transmitted beam.

The results indicated that the best laser wavelength was 1.622 microns, and the second best wavelength was 1.06 microns (See Fig. 6). The Navy is currently developing a solid state laser at 1.622 microns under a Phase II SBIR with Schaffer Corporation, and high power solid state lasers at 1.06 microns are currently under development by the DoD. The one major surprise from the DS&S study was that CO_2 lasers using either carbon dioxide or isotopic carbon dioxide at (e.g., 10.6 or 11.2 microns respectively) lost so much power by the time they reached the extreme distances (i.e., >500 km) required for launching payloads that they could not reach orbit with any payload.

The results of the Flight Unlimited study also indicated that specific impulse values approaching 1,000 s would be required to launch payloads into space. At this time it is unclear whether or not a solid fuel or a liquid fuel will be used for the non-airbreathing portion of the launch trajectory. However, both paths are being pursued independently. Mr. Schall and Dr. Hans-Albert at the DLR in Stuttgart, under a European Office of Aerospace Research & Development (EOARD) contract, are pursuing the solid propellant approach, and Dr. Uchida at Osaka University under an Asian Office of Aerospace Research & Development (AOARD) research contract is pursuing the liquid propellant approach. Both research programs are developing ablative propellants that can deliver the high specific impulse values required to launch payloads into space.

X-vehicle fabrication is done by COI Ceramics in San Diego CA. At COI, Dr. Tim Easler supervises a team of materials scientists who have developed the technology required to make all composite, lightweight X-vehicles. The first assemblies, made with Nicalon, have been heavy and a little rough because of the component's complexity. But subsequent assemblies should be considerably lighter, being stronger and more heat resistant than Aluminum.

In May 2000, the AFRL initiated a Phase I Small Business Innovative Research (SBIR) contract with SY Technology, Inc., in Huntsville AL, to start the development of a lateral control and angular pointing system for the X-25LR. Lateral control is required to keep the vehicle properly positioned in the laser beam throughout its launch into orbit. Angular control is required to keep the vehicle oriented properly with respect to the beam (i.e., pointed at the GBL).The X-25LR vehicle was selected for developed at this size, quarter scale, for the development of the attitude control system. The Phase I goal was to determine the requirements of the control system and then to design and demonstrate control technologies which meet these requirements. This work was completed in January 2002.

In February 2003, the AFRL initiated a Phase II SBIR with Polaris Sensors, Inc., which is a derivative of SY Technology, Inc., to develop and demonstrate with flight tests at WSMR an initial version of their attitude control design concept. The program is funded for two years and then will require additional funding and time to complete the flight demonstration by March of FY 2006. This program will be revolutionary. Laser propulsion vehicles have never been controlled to this degree, and estimates indicate that the X-25LR demonstration vehicle should be able to attain altitudes in excess of 1,000 ft using the 10 kW PLVTS laser at WSMR.

The Navy has recently become interested in laser propulsion. At Dahlgren VA, Mr. Mike Libeau has initiated a study program to assess the advantages to the Navy in using laser propulsion. The Navy will be able to leverage Air

Force technology to develop their own class of vehicles. And the Navy is developing the 1.622 micron high power solid state laser that should make an ideal power system for beaming energy to launch vehicles.

The schedule for the X-50LR program is shown in Figure 7. The "cream" colored bars indicate the funded effort as it currently exists, and the yellow bars indicate tasks that will require additional resources in order to be completed. The schedule shows that at the present, the program will end in September of 2006, and a final report will be written and distributed by September of 2008. If additional funding can be obtained, the Polaris Sensors attitude control system will be demonstrated with a flight test program at HELSTF covering the period from about December 2005 to July 2006. This has a good chance of happening and will extend the approved program into 2007.

Also, Figure 7 shows that a 100 kW laser design study was completed in December 2002. The study was done by Textron, MA.[8] A 100 kW laser is required to accomplish the X-50LR program goal of vertical launches to 30 km and above. The design study produced four possible assembly combinations using CO_2 laser hardware currently available at HELSTF – two Coherant Radar Amplifier (CORA) lasers in storage and two PLVTS lasers, one of which is in storage. The costs of each approach also derived during the study ranged from $12M to $16M.

In addition, a 3-meter diameter beam director with adaptive optics will be required to project sufficient laser energy to the altitudes under consideration. Figure 8 illustrates the vertical beam propagation calculations in the vertical direction as a function of spot size for 3.8, 10.6, and 11.2 micron wavelengths using a 3-meter beam director. It can be seen in the figure that the spot size at 30 km altitude, a yellow "dot" indicates the design point, is sufficient to pass through the rear orifice of a 50-cm ramjet. Thus, if the funding for the 100 kW laser and the 3-meter beam director can be obtained, there is a good chance that vertical sounding ramjet flights to the edge of space could be accomplished by the end of FY 2009. We are currently searching for the funding to support this high altitude flight demonstration of a laser-propelled ramjet.

3. Summary

X-25LR vehicles will continue to be utilized for experimental laboratory and flight tests for at least another two years before the AFRL terminates its laser propulsion effort. If a 100 kW laser can be assembled with a 3-meter beam director, the X-50LR scale-up work will be initiated with the expressed goal of launching payloads vertically in sounding rocket trajectories to space by the end of FY 2009. If not, a final report covering the entire program will be completed by the end of FY 2008, and this technology will be shelved until a later time when it is considered more appropriate.

The main conclusion of the Flight Unlimited Study was that a megawatt-class solid state laser operating at 1.622 microns would be capable of launching several kilograms into low-Earth-orbit. To really be a valid concept for space launch, high power solid state laser technology must be available for megawatt class lasers. Solid state lasers of this magnitude are at least a decade or more away from development. Predictions on their cost indicate that they will cost hundreds of millions of dollars, so there must be a good reason for an investment of that magnitude. Thus, the market for small, inexpensive payload launches to orbit must be desirable before the Government or private enterprise will be willing to make such an investment.

4. References

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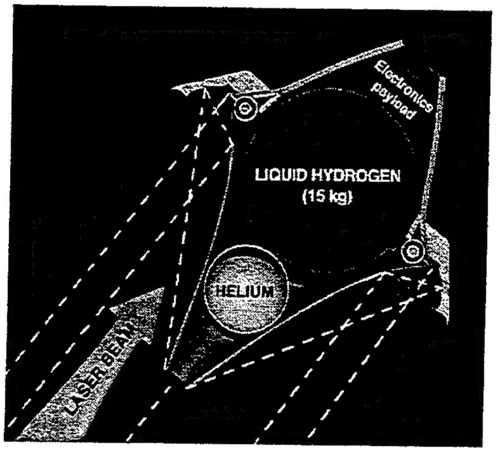

Figure 1. The SDIO Lightcraft

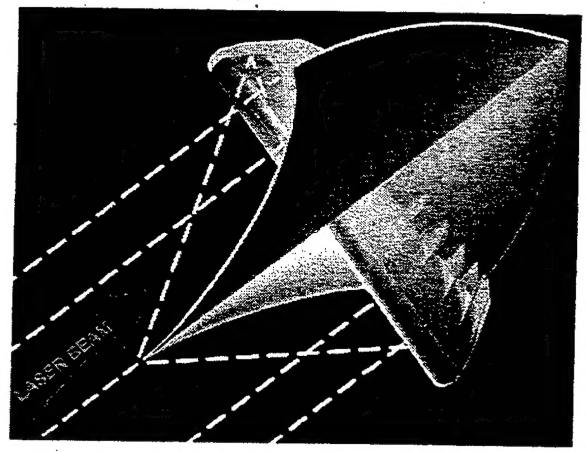

Figure 2. Cutaway of LTD Flight Model

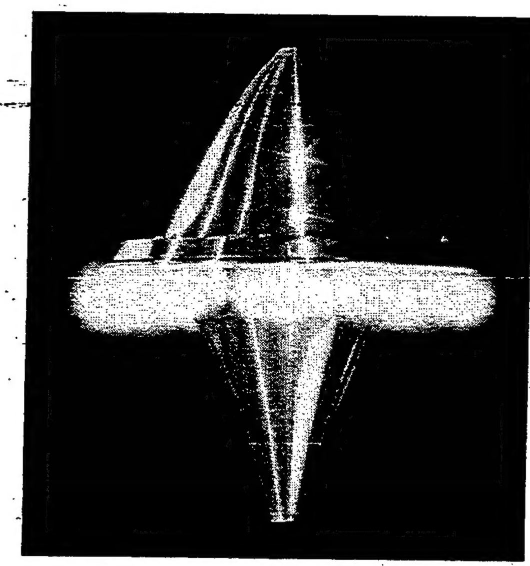

Figure 3. Plasma Ejection From an LTD Vehicle

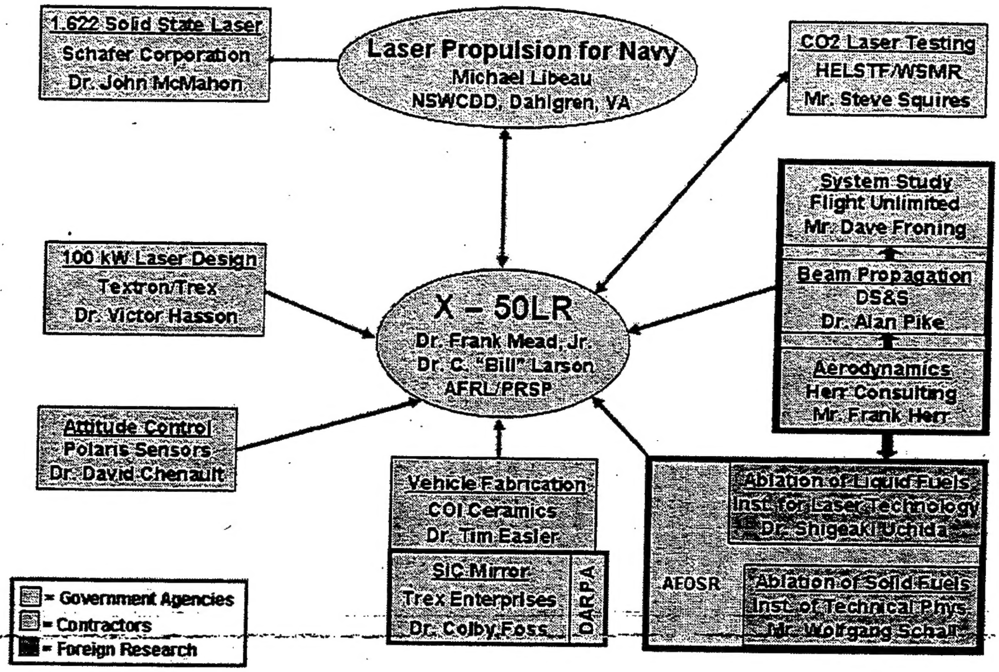

Figure 4. X-50LR Collaborations

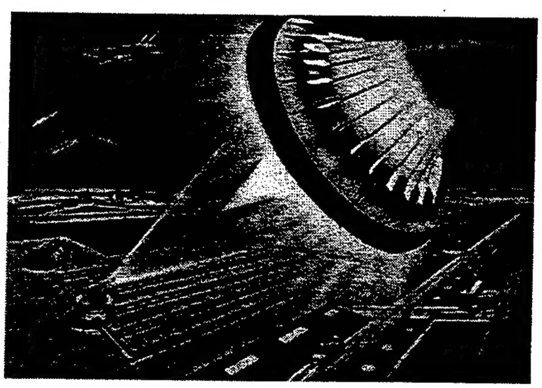

Figure 5. SSTO Beam Rider Launch

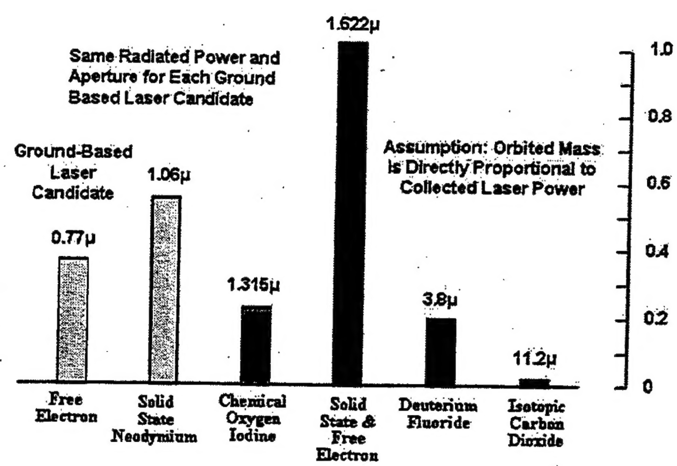

Figure 6. Wavelength Impact on Mass to LEO

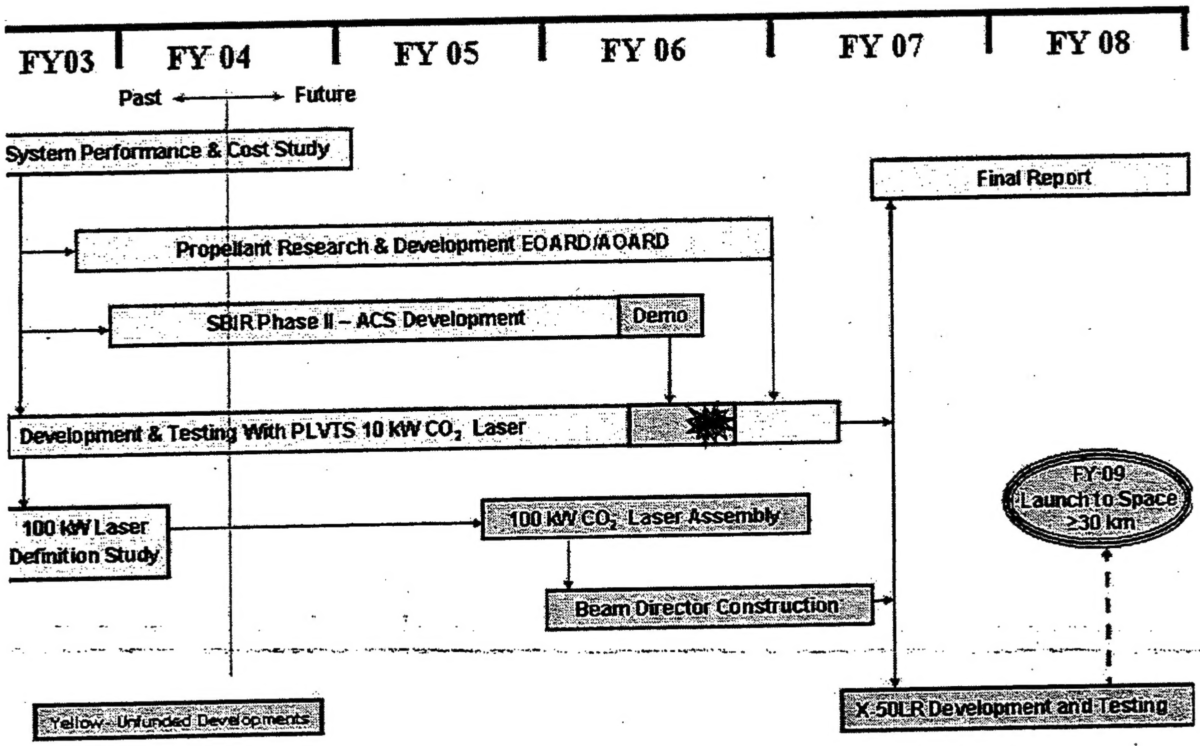

Figure 7. X-50LR Schedule

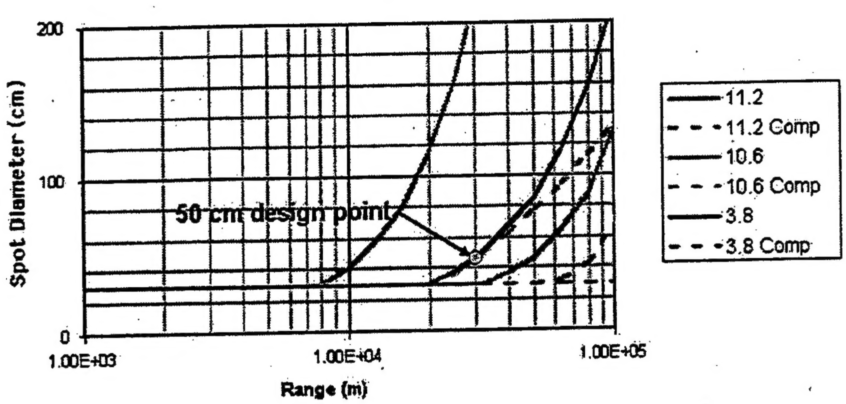

Figure 8. 3-m Beam Director Spot Sizes